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Comments on the MIT Assessment of the Mars One Plan

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The MIT assessment of the Mars One mission plan reveals design assumptions that would cause significant difficulties. Growing crops in the crew chamber produces excessive oxygen levels. The assumed in-situ resource utilization (ISRU) equipment has too low a Technology Readiness Level (TRL). The required spare parts cause a large and increasing launch mass logistics burden. The assumed International Space Station (ISS) Environmental Control and Life Support (ECLS) technologies were developed for microgravity and therefore are not suitable for Mars gravity. Growing food requires more mass than sending food from Earth. The large number of spares is due to the relatively low reliability of ECLS and the low TRL of ISRU. The Mars One habitat design is similar to past concepts but does not incorporate current knowledge. The MIT architecture analysis tool for long-term settlements on the Martian surface includes an ECLS system simulation, an ISRU sizing model, and an analysis of required spares. The MIT tool showed the need for separate crop and crew chambers, the large spare parts logistics, that crops require more mass than Earth food, and that more spares are needed if reliability is lower. That ISRU has low TRL and ISS ECLS was designed for microgravity are well known. Interestingly, the results produced by the architecture analysis tool - separate crop chamber, large spares mass, large crop chamber mass, and low reliability requiring more spares - were also well known. A common approach to ECLS architecture analysis is to build a complex model that is intended to be all-inclusive and is hoped will help solve all design problems. Such models can struggle to replicate obvious and well-known results and are often unable to answer unanticipated new questions. A better approach would be to survey the literature for background knowledge and then directly analyze the important problems.

Nomenclature

<i>ECLS</i>	=	Environmental Control and Life Support
<i>ESM</i>	=	Equivalent Systems Mass
<i>ISRU</i>	=	In-Situ Resource Utilization
<i>ISS</i>	=	International Space Station
<i>LL</i>	=	Life Limit
<i>MTBF</i>	=	Mean Time Between Failure
<i>TRL</i>	=	Technology Readiness Level

I. Introduction

THIS analysis discusses the MIT critique of the Mars One plan, which shows that Mars One makes mission design assumptions which make its approach doubtful. Some problems with Mars One are that growing crops in the crew chamber produces oxygen levels too high for the crew, that the assumed in-situ resource utilization (ISRU) equipment has a low Technology Readiness Level (TRL), that the spare parts required for reasonable reliability cause a significant and increasing launch mass logistics burden, that the assumed International Space Station (ISS) Environmental Control and Life Support (ECLS) technologies were developed for microgravity and so are not suitable for Mars gravity, and that grown food requires more launch mass than stored food. The large number of spares is due to the relatively low reliability of ECLS and the low TRL of ISRU. These findings by the MIT group cast doubt on the feasibility of Mars One base concept and show it does not reflect the best current understanding of Mars habitat design. The Mars One mission plan and life support system are described in an appendix.

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The MIT authors used their previously developed architecture analysis tool that considers long-term settlements on the Martian surface. It includes an ECLS system simulation, an ISRU sizing model, and an analysis of the required number of spares. It produced the results that showed the need to separate crop and crew chambers, the high spare parts logistics burden, that growing food requires more mass than stored food, and that more spares are needed when reliability is lower. The other points that ISRU has low TRL and that ISS ECLS was designed for microgravity are obvious and well known. Interestingly, the results produced by the architecture analysis tool can also be considered obvious and well known, having been previously published. The MIT model, although sophisticated and obviously useful, itself does not fully reflect the current understanding of Mars habitat design.

Building a complex, all-inclusive model that can support design has been a frequent objective of ECLS analysis. Integrated models are very useful in investigating and optimizing a defined systems architecture. Large ECLS system models are plausible, fundable, and publishable. They provide a good way to gather, organize, and communicate ECLS design information. However, such models often struggle to replicate obvious and well-known results and can rarely handle new problems outside their original scope. It seems that for many problems, a direct analysis or a narrowly targeted simulation would be more cost-effective.

II. The MIT assessment of the Mars One project is valuable

In October 2014, MIT student researchers in space life support and their professor published their analysis of the Mars One initiative, “An Independent Assessment of the Technical Feasibility of the Mars One Mission Plan.” (Do, et al.) It deservedly received wide attention in space and popular publications, including NASA Watch, Space Policy Online, and Popular Mechanics. Its overall implication, that Mars One as planned was not feasible, was generally accepted with one article titled, “MIT Analysis Paints Bleak Outcome for Mars One Concept.” (Smith)

Mars One and the MIT assessment of it returned to the news in February, 2015, when 100 Mars One colonists were selected. The space policy expert John Logsdon said, “It looks like a scam.” (Vergano) One important effect of the MIT assessment is to prevent the problems of Mars One causing doubt about all Mars initiatives. Some claim that, “Mars One’s flaws - too few spaceships, nonexistent life-support technologies, not nearly enough money, and, really, no good reason for going - discredit all Mars exploration plans, including NASA’s.” (Vergano) But not all Mars plans are as vulnerable to serious criticism as Mars One. The MIT assessment finds “technology development will have to focus on improving the reliability of ECLS systems.” (Do et al., p. 25) NASA associate administrator for human exploration and operations William Gerstenmaier said of the MIT study, “That’s a very intriguing report.” “What it describes to us is how difficult sustaining humans on another world is really going to be.” (Foust)

1. Mars One objects to the MIT assessment

Bas Lansdorp, the Dutch founder of Mars One,

“said the MIT analysis had included “preposterous decisions” on the design of the simulation, which had led to incorrect conclusions. He said these would be challenged by a new assessment by Paragon Space Corporation, commissioned by Mars One. “They’ve been wrapping up their own study, which will be out in early March. They called the MIT analysis ‘very naïve.’ ” (Devlin)

2. The MIT assessment is essentially correct despite minor objections

The MIT simulation could have made assumptions more favorable to Mars One, but Mars One’s combining the crew and crops in one chamber was an obvious difficulty. So was planning to grow crops in the first place. The MIT assessment can be faulted for various technical reasons, but it reflects a more thorough and correct assessment of the issues than the Mars One plan.

This paper’s technical review of the MIT assessment of Mars One is much less important than the MIT work itself. The investigation here is concerned with details, precedents, and techniques. It does not dispute the MIT assessment’s general conclusions or diminish their importance. This work attempts to suggest a better approach to Mars habitat design and assessment, less modeling and more literature research than was done by MIT. The MIT assessment was timely, important, and necessary.

III. The Mars One plan seems flawed

The Mars One plan initially seems plausible but does not seem to have been examined in detail. Mars One planning does not seem to reflect the space program technical literature which includes life support analysis and NASA’s past mission plans. It does not incorporate current understanding of Mars missions. Logsdon notes, “They don’t have any technology, they don’t have any agreements with the space industry. It looks very shaky.” (Vergano)

The MIT assessment uncovers some unrealistic assumptions and unsolved problems in the Mars One approach. These are combining crew and crops in one chamber, ISRU readiness, spare parts logistics, ECLSS readiness, and growing food.

1. *Combining crew and crops in one chamber produces too high oxygen levels*

The MIT assessment states,

“the first crew fatality would occur approximately 68 days into the mission. This would be a result of suffocation from too low an oxygen partial pressure within the environment... this non-intuitive result is primarily caused by the plants producing excessive oxygen, increasing oxygen partial pressure to outside their partial pressure control box, and causing the pressure control assemblies to vent air.” (Do et al., p.10)

Mars One defenders can correctly claim that venting atmosphere to reduce the high oxygen partial pressure produced by the crop plants is not reasonable, especially since it results in the loss of the atmosphere and the death of the crew.

The MIT assessment suggests one solution to this problem is “using a separate enclosed plant chamber to decouple the variations in atmospheric composition generated by the plants to those of the crew. (Do et al., p. 11) The difficulties of combining crew and crops and the benefits of separating them are obvious and well known, as described in the paper, “Modeling Separate and Combined Atmospheres in BIO-Plex.” (Jones et al., 2001-01-2361) It is possible but difficult to use a single combined chamber for plants and crew. The MIT crop growth simulation using separate chambers was successful. (Do et al., pp. 12-14) Perhaps MIT could have assumed the Mars One would revise its approach in this way, but Mars One should have been aware of the problems and presented a workable design.

2. *The ISRU for Mars has a low TRL*

The MIT assessment states,

“ISRU technology is at a relatively low TRL... As a result of this, there is a high uncertainty in the reliability and size of ISRU systems. (Do et al., p. 4)

It is obvious that “the ISRU technology required to produce nitrogen, oxygen, and water on the surface of Mars is at a relatively low TRL.” (Do et al., pp. 1, 25) And clearly the cost and reliability of ISRU is unknown. Mars One makes strongly optimistic assumptions that show insufficient appreciation of the difficulties with ISRU.

3. *The ECLS and ISRU spare parts require very high launch mass*

The MIT assessment states,

“A spare parts analysis revealed that spare parts quickly come to dominate resupply mass as the settlement grows.” (Do et al., p. 1) “For each subsequent crew, the mass of spares increases due to the increased number of systems operating on the surface.” (Do et al., p. 21) (T)he amount of mass required by the system increases with the number of crews on the surface. This is due to the fact that each crew of 4 is supported by their own ECLS and ISRU. The number of spares calculated ... applies to a single system supporting a single crew. When the second crew arrives, two systems will be in operation, requiring twice as many spares, and so on for each subsequent crew. (Do et al., p. 22)

The Mars One website notes this challenge, stating that “for a long time, the supply requests from the outpost will be for complex spare parts, which cannot be readily reproduced with the limited technology on Mars.” (Do et al., p. 22)

The assumptions made in the MIT assessment exaggerate the number of spares needed. As stated, each crew has its own primary ECLS and ISRU systems and a complete set of spares for each. When N crew are on the surface, there are N operating systems and N sets of spares. The MIT assessment notes that spares can be shared but does not plan to share them.

“This is a first-order estimate of mass requirements based on the need to provide the same level of assurance to each crew, and could be somewhat reduced by taking advantage of commonality between the different Life Support Units and informing spares manifesting based on the performance of the surface systems up until the launch date. However, the inescapable truth is that as more systems are deployed and operated on the surface of Mars, more spares will be required to maintain them.” (Do et al., p. 22)

That sharing reduces the required number of spares is well known. Calculations in the Appendix and a previous MIT study cited there indicate that sharing would reduce the required number of spares roughly by half. It is therefore less certain that “(S)pare parts quickly come to dominate resupply mass as the settlement grows.” (Do et al., p. 1) The portion of spares in resupply would depend on the equipment mass, lifetime, and failure rate, and might not be much larger than the crew food requirement. Very reliable, long life equipment would require infrequent repair and replacement and impose a small logistics burden. Less reliable, shorter life equipment could require a larger logistics mass that would grow proportionally to the number of crews and the number of actually operating systems on Mars. Clearly the spare and replacement parts can be a significant logistics burden and the MIT assessment correctly concludes, “(T)echnology development will have to focus on improving the reliability of ECLS systems.” (Do et al., p. 25)

4. *The ISS ECLSS technologies were developed for microgravity, not Mars gravity*

The MIT assessment states,

“(T)he ECLS technologies developed for the ISS were specifically developed to perform in microgravity. The introduction of a partial gravity environment will inevitably lead to different ECLS technologies.” (Do et al., p. 6)

Another reason to anticipate different Mars technologies will differ from ISS is the need for much higher reliability and maintainability on Mars.

The MIT assessment states,

“The continued operation of the ISS is dependent upon regular (and even unplanned) resupply of replacement parts from Earth, and in the event of an unrecoverable system failure the crew have the option to quickly return to Earth. On Mars, ... there will be no feasible option for the crew to return to Earth in a timely manner. The ability of the crew to repair the systems that sustain them ... is critical to mission safety.” (Do et al., p. 16)

It seems obvious to the MIT authors and many others that different and intrinsically higher reliability ECLSS technologies will be needed for Mars, but some hope that improving ISS ECLSS will suffice. Thus Mars One’s claim that its life support units will “be very similar to those units which are fully functional on-board the International Space Station,” (Do et al., p. 6) would have supporters. The Mars One planners and other advocates of using ISS ECLSS systems for Mars are clearly very optimistic and could be criticized for not acknowledging the obvious problems or developing coherent plans for solving them.

5. *Growing food would require more launch mass than stored food.*

The MIT assessment states,

(T)he use of a BPS (Biomass Production System) for food production does not pay off in terms of system mass within a reasonable time horizon. Even after two decades of operation, the BPS option still results in significantly more mass delivered to Mars than SF (Stored Food). (Do et al., p. 22)

Both Mars One and MIT assumed that crops would be grown without first assessing its feasibility. The fact that growing food requires more launch mass than stored food from Earth is well known, as described in the paper, “Comparison of Bioregenerative and Physical/Chemical Life Support Systems.” (Jones, 2006-01-2082) Many decades must pass before growing food saves mass. The facts that Mars One assumed food would be grown, and that the MIT group developed an extensive simulation of Mars crop growth chambers, suggest that both did not consider this result.

IV. Looking forward to a mission to Mars

The MIT assessment of Mars One is an important contribution to Mars mission planning. The Mars One project approach has been clearly challenged by MIT’s strong specific criticisms. Hopefully Mars One will improve their approach. Yet much more remains to be done.

1. *Other plans for Mars*

The Mars One plan has some omissions and oversights and it would be valuable to analyze more detailed and better developed plans. Connelly’s “Mars Design Example” in Human Spaceflight is quite detailed. (Connelly). NASA’s Mars Design Reference Architecture 5.0 was developed in 2009 during the Constellation program. Although clearly obsolete because of its reliance on a moon base precursor, it remains the latest. William Gerstenmaier said in January, 2015, “If you asked me how we would go to Mars today, I’d pull out design reference architecture number five.” (Foust)

2. *How should a permanent Mars base be established?*

If the fundamental assumption of Mars One is correct, that it is more desirable to maintain a crew on Mars than to bring it back to Earth, then the obvious question is, “How should a permanent Mars base be established and maintained?” The overall concept would depend on the goals and objectives identified for the base, but the engineering concern is similar for any long human stay, “What is the safest, cheapest way?” The approach would probably use pre-emplaced stores and ECLSS and ISRU equipment, as envisioned by Mars One. Crop growth is uneconomical compared to stored food and would produce a much less satisfactory diet, as noted in the MIT assessment and elsewhere. The MIT analysis suggests that the spares should not be full units or ORUs, but lower level components or subassemblies to minimize mass. (Do et al., p. 17) A recent analysis finds that common cause failures can limit the benefit of using identical spare parts and that full system spares using diverse technology would be better. (Jones, 2015-047)

3. *Is the best type of mission a permanent base?*

The more fundamental question is, “How should humans visit Mars?” The Connelly example and the NASA design reference mission assume a long, roughly 500 day surface stay, but alternatives include a short surface stay, a fly by, and Mars moon visits as well as no-return trips similar to Mars One. Most of the alternate mission plans would cost less and provide fewer benefits than the usually proposed long stay surface mission, but over time a permanent base would have much greater costs and benefits than any fixed duration mission. Which is the best first Mars mission? Should there be a planned sequence of missions? Regardless of which mission is first, it will require improved, more reliable life support.

V. Should space architecture analysis use integrated models?

The MIT study group used its Mars One assessment to present their architecture analysis tool, and it produced the key results that a combined crew and crop chamber produced excessive oxygen levels, that low component reliability produced a high spare parts logistics burden, and that growing food required more launch mass than stored food from Earth. The other important observations, that ISRU has low TRL and ISS ECLSS is designed for microgravity, not Mars, were presumably made during preliminary research for the model. More extensive and detailed research would also have found that the architecture analysis tool results on shared chamber oxygen levels, high spare parts logistics, and grown food being uneconomical, were also well known. Although it was useful in replicating Mars One, there was no real need for the MIT architecture analysis tool to include combined crew and crop chambers or detailed crop growth modeling. And the spares analysis omitted the effect of shared spares, also obvious and well known.

A systems level model should not be an integrated set of detailed subsystem models. The MIT model has detailed components, such as human metabolism and crop growth, which in usual practice would have been abstracted to a higher level and represented by black boxes.

Building large, complex, detailed, inclusive models is very popular in academia and government. Such models are plausible, fundable, publishable, and make great demos. Developing them is far more interesting than library research. Managers love models, even though or perhaps partly because developing them postpones the difficult work of solving real problems. All models are simplified representations of the real world and they often leave out important factors that are difficult to model, such as reliability and cost. Models can fail to reproduce obvious and well known facts. They are usually much more elaborate than needed to answer the few questions they can answer. New kinds of problems are often “out of the model” and require the model to be augmented. Models should be constructed to answer defined questions and not expected to do more. Models built in the hope of producing unpredictable, enlightening new results often fail to do so. A model should not be an end in itself, but a tool to solve a problem.

The best approach in systems engineering is to identify and attack problems directly. Many real world problems can be solved by inspection, a back-of-the-envelope analysis, a literature search, or a quick simulation focused on a specific problem. Constructing a model to solve a specific known problem is much more effective than constructing a highly detailed, all-inclusive general purpose model to solve undefined problems.

VI. Conclusion

The key result of the MIT assessment of the Mars One project is the demonstration that the Mars One plan can be questioned. It does not reflect a thorough understanding of Mars habitat design. The MIT assessment calls out some specific problems; combining crew and crops in a single chamber, low TRL for ISRU, high logistics mass burden for spare parts, ISS ECLSS technologies developed for microgravity not Mars, and grown food requires more launch mass than stored food. The MIT assessment has cast strong doubt on the current Mars One plan. Mars One should reassess its approach.

The question then becomes, “How should a permanent Mars base be established and maintained?” And, “What is the safest, cheapest way?” A large mass of spares will be required to support Mars habitat systems unless much work is done to improve their reliability before the mission. A permanent Mars base would be more expensive and challenging than brief visits. Probably fly-bys and brief visits should come first.

The key detailed MIT results were produced using an overall architecture analysis tool for Mars settlements, but similar results had previously been found by analysis and simulation that focused on these particular problems. Directly trying to solve specific identified problems is usually much more effective than constructing an inclusive general purpose model and running it to find problems. Often the needed results can be found by a literature search or quick calculation.

Appendix: The Mars One mission plan and life support system

The MIT team analysis of the Mars One mission plan was based on their review of Mars One published material and further needed assumptions. The Mars One mission time line and life support system are described below according to the MIT analysis. (Do et al.) Mars One has disputed some of the MIT assumptions and they may not consider their own published plans to be final.

Mars One plans to send a four-person crew to Mars in 2025 and another crew at every 26 month interval launch opportunity in the future. The crews would not return to Earth but would remain on Mars for the rest of their lives. The no-return concept saves the cost of the return habitat, rocket, and propulsion. Continuing launches will be required to sustain the Mars One settlement. Each crew on landing would enter its own identical pre-emplaced Mars

One habitat, so another four-person habitat must be sent before the crew every 26 months. All the crews and habitats would be sent to the same location on Mars. The habitats would be connected to form a single constantly growing Mars settlement.

Unmanned precursor missions would test and deploy needed technologies, prepare the site, and emplace the first habitat before the first crew is sent to Mars. Solar power, water extraction from the soil, surveyor rovers, site grading equipment, and a communications satellite would be implemented.

Each habitat would consist of six independently launched modules, with three pairs of identical units. The two living units have crew quarters, waste and hygiene facilities, and an airlock. The two life support units have solar arrays, ISRU equipment, ISS technology life support systems for air revitalization, oxygen generation, water recycling, waste management, and a crop growth facility. Two cargo units store supplies and spare parts.

The Mars One habitat life support units would have thin-film solar arrays for power. The ISRU element uses a rover that delivers Martian soil to an oven in the life support unit, where it is baked to extract water. The air revitalization, oxygen generation, water recycling, and waste management systems are presumed to be similar to those used on ISS, even though the ISS systems were developed for zero gravity. As on ISS, oxygen generation uses Solid Polymer Water Electrolysis, carbon dioxide is removed by a Molecular Sieve and reduced by a Sabatier Reactor, humidity is removed by a Condensing Heat Exchanger, and wastewater is processed by Vapor Compression Distillation and Multifiltration. The crop growth facility is expected to provide all of the food, even though this is usually considered difficult and uneconomical.

Appendix: The required number of shared spares

The MIT analysis found that the “as the settlement grows: after 130 months on the Martian surface, spare parts quickly come to dominate resupply mass” for the life support and ISRU systems. (Do et al., p. 1) Sufficient spare parts were required to provide 0.99 reliability, based on the components’ mean time between failure (MTBF) and life limit (LL). The number of spare parts required for units reaching their LL is simply mission time/LL. The number of spare parts required to replace random failures was calculated using a Markov model with probabilistic transitions to failed states and repairs to return to normal. (Do et al., pp. 16-18) Nearly all the spares were required to repair random failures, and some parts such as valves and sensors required a dozen or even several dozens of spares. (Do et al., pp. 34-35) The large number and mass of spares is due to the relatively low reliability of ECLSS and the low TRL of ISRU which leads to a low estimated reliability. (Do et al., p. 24) Much more work is required to advance TRL and improve the reliability of Mars habitat systems before a Mars mission. (Do et al., p. 25)

However, as mentioned, the number and mass of spares is overestimated since spares are not shared between crews, “and could be somewhat reduced by taking advantage of commonality between the different Life Support Units.” (Do et al., p. 22)

After 130 months, five crews of four persons each would be on the Martian surface, each with their own life support and ISRU systems and each with their own full sets of spares! One of the great advantages of operating many identical systems is that fewer spares are required to ensure continued operation. Spares are essentially insurance and are typically rarely used. Using individual dedicated spares for identical units is unnecessary and wasteful.

The savings due to shared or floating spares for the first five crews can be determined. For simplicity, assume that full system spares are provided rather than subsystems. The first crew will have one original system and one dedicated identical spare. Since the systems must provide the required reliability of 0.99, each system, original and spare, must have a reliability of 0.9. Assume for ease in calculation that both the original and spare systems are operating full time. If each one has a probability of failure, over its system lifetime, of 0.1, the probability that both will fail is $0.1 * 0.1 = 0.01$, so the overall reliability is 0.99 as required.

If the assumed approach is to send five crews, each with one original system and one dedicated identical spare, there will be five systems and five spares. Each crew is on its own and the spare systems are not shared, so each crew has a probability of success of 0.99 and a probability of failure of 0.01. The total probability of failure for all five crews is $5 * 0.01 = 0.05$. The overall reliability, the probability of Mars One success to that point, is 0.95. Sharing the spare systems would improve this.

1. Binomial distribution

A “r out of n” redundant design has “n” identical systems that operate or fail independently. The overall system operates as long as any “r” systems do not fail. Suppose all the systems are identical with the same probability of failure and reliability. The probability that exactly x systems survive to time t is given by the binomial pdf, assuming that the individual system probability of success is p.

$$\text{Binomial pdf (x survive)} = [n!/x!(n-x)!] p^x (1-p)^{n-x}$$

x survive, n-x fail, and there are n!/x!(n-x)! different permutations of the x surviving systems.

The overall reliability, R, is the probability that r or more up to n systems survive. This is the cumulative binomial distribution from i = r to n.

$$R = \text{SUM}[i = r \text{ to } n] \{ [n!/i!(n-i)!] p^i (1-p)^{n-i} \}$$

For the first crew, r = 1, n = 2, p = 0.9, and the cumulative binomial distribution gives R = 0.99. For five crews, r = 5, n = 10, p = 0.9, and the cumulative binomial distribution gives R = 0.9984. The benefit of sharing spares is to increase the probability of all crews surviving from 0.95 to 0.9984. If an overall probability of all surviving of 0.95 was acceptable, the number of spares could be reduced from 5 to 3, producing an R = 0.9619 probability of all crews surviving.

The number of spares does not have to increase as rapidly as the number of crews and becomes proportionally less for an increasing number of crews. This result was achieved using hot spares, operating full time. This allowed the above simplified analysis to avoid the issues of the failure occurrence times and required mission length. It is much more efficient to use cold spares, since they can be assumed to have a negligible failure rate while they are not operating. The probability of a given number of failures using cold spares is given by the Poisson distribution.

2. Poisson distribution

It was shown that, for a first crew reliability of 0.99, the original and a hot spare must each have a probability of failure over the mission time of 0.1. For one operating unit and one cold spare with the same 0.1 probability of failure, the Poisson distribution shows that the probability that both units fail is 0.005. The failure probability is reduced by half, since one unit is not operating and so has an assumed zero probability of failing. This means that the individual systems can each have a probability of failure over the mission time greater than 0.1.

To use the Poisson distribution, we will assume that the system lifetime is limited to ten years and that then all systems are replaced. To avoid the complexity of time staggering, we assume that the five crews are emplaced simultaneously on Mars. Then the reliability requirement applies to all crews and systems over a period of ten years. Suppose the original system has a failure rate, λ , the number of times it is expected to fail per year. The cumulative number of failures from time 0 to time t is n(t) and has a Poisson distribution.

The Poisson pdf gives the probability, for failure rate λ , that there will be exactly n(t) = x failures in time t.

$$\text{Poisson pdf } [n(t) = x] = (\lambda t)^x e^{-\lambda t} / x!$$

The Poisson distribution's mean value, which is the expected number of failures during the mission of length t, is λt . The probability of n(t) or fewer failures is the summation of the Poisson pdf from x equals 0 to n(t). The probability of n(t) or more failures is the summation of the pdf from n(t) to infinity.

For a single crew case, we have two systems and to avoid failure must have either 0 or 1 failures with a probability of success of R = 0.99. This can be achieved with a mean value of $\lambda t = 0.15$, corresponding to the probability of 0.15 failures over the 10 year mission length. This is 50% larger than the 0.1 failure rate over the system lifetime that was needed with a hot spare.

For five systems running, the expected number of failures is $5 * 0.15 = 0.75$. With five crews with five systems and five cold spares, the probability of 5 or fewer failures would be 0.9999. The probability of three or fewer failures would be 0.9927, so only three spares would be required to achieve an overall probability of all five crews surviving greater than 0.99. This is the same number of spares as required for hot spares, but the systems can now be significantly less reliable, with a failure probability of 0.15 rather than 0.1. If the systems had the original lower failure probability of 0.1 per system over the system lifetime, the expected number of failures for five systems running would be lower, 0.5. Two spares make the overall probability of all five crews surviving equal to 0.9856, nearly the required 0.99.

The number of spares depends on the assumed system reliability, but would be about one-half the number calculated in the MIT assessment using their assumed reliability. This was explained in an earlier MIT study.

"The logistics resources (in the form of spare parts) for future exploration missions to the Moon and Mars can have significant mass and volume requirements. In this study it is shown that reconfigurable or common parts, that allow use of the same component in different mission elements, can be a means of reducing the required number of spares. A model

for determining the system availability as a function of spares level is developed for a mission that utilizes elements with reconfigurable or common parts. An explicit consideration of the operating scenario is made which allows for using components from elements that are not operating at a given time. A Mars surface exploration mission is used to illustrate the application of this model. It is shown, for the specific example studied in the analysis, that the same level of system availability can be achieved with 33% - 50% fewer spares if the parts are reconfigurable or common across different mission elements.” (Siddiqi and de Weck)

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